

AD-768 748

A RELIABLE PIEZOELECTRIC BALLISTIC IMPACT
DETECTOR

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Washington, D. C.

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UNCLASSIFIED

Security Classification

AD 768748

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Naval Research Laboratory Underwater Sound Reference Division P.O. Box 8337, Orlando, Fla. 32806		2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	
		2b. GROUP	
3. REPORT TITLE A RELIABLE PIEZOELECTRIC BALLISTIC IMPACT DETECTOR			
4. DESCRIPTIVE NOTES (Type of report and inclusive dates) Final report on part of the problem.			
5. AUTHOR(S) (First name, middle initial, last name) Larry E. Ivey Theodore A. Henriquez			
6. REPORT DATE 25 October 1973	7a. TOTAL NO. OF PAGES ii + 16	7b. NO. OF REFS 5	
8a. CONTRACT OR GRANT NO. NRL Problem S02-36.401	8a. ORIGINATOR'S REPORT NUMBER(S) NRL Report 7664		
b. PROJECT NO. NTEC Work Request WR 1-0091 of 25 Mar 1971	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)		
c.			
d.			
10. DISTRIBUTION STATEMENT Approved for public release; distribution unlimited			
11. SUPPLEMENTARY NOTES		12. SPONSORING MILITARY ACTIVITY Naval Training Equipment Center Orlando, Fla. 32813	
13. ABSTRACT A unique piezoelectric device has been developed to meet the Army's need for a more effective and economical sensor for the hit detection system used on rifle and tank firing ranges. The new sensor was designed to replace a relatively expensive unit that works well on a sheet metal target but is difficult to install and is not adaptable to cheaper target materials. Exceptional protection is provided for the sensitive element by a simple mounting assembly consisting of a pair of stainless-steel washers clamped around the element with a single bolt and wingnut fastener. Field tests showed that the new sensor is not only a more effective impact detector than the original sensor, but is capable of discriminating against false indications that may be caused by muzzle blast, debris thrown against the target by near misses or short rounds, and vibrations from other causes such as wind. Costing less than half as much as the original sensor, the new unit promises the additional economies of low maintenance and replacement costs on the basis of its durable performance in rifle firing tests. One unit continued to operate even after sustaining a direct hit.			

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DD FORM 1473

1 NOV 65

(PAGE 1)

S/N 0102-014-0600

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UNCLASSIFIED
Security Classification

UNCLASSIFIED

Security Classification

14

KEY WORDS

Piezoelectric ceramics
Ballistic impact detectors
Transducer mounting
Attenuation
Longitudinal waves
Transverse waves

LINK A

LINK B

LINK C

ROLE

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ROLE

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UNCLASSIFIED
Security Classification

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Abstract

A unique piezoelectric device has been developed to meet the Army's need for a more effective and economical sensor for the hit detection system used on rifle and tank firing ranges. The new sensor was designed to replace a relatively expensive unit that works well on a sheet metal target but is difficult to install and is not adaptable to cheaper target materials. Exceptional protection is provided for the sensitive element by a simple mounting assembly consisting of a pair of stainless-steel washers clamped around the element with a single bolt and wingnut fastener. Field tests showed that the new sensor is not only a more effective impact detector than the original sensor, but is capable of discriminating against false indications that may be caused by muzzle blast, debris thrown against the target by near misses or short rounds, and vibrations from other causes such as wind. Costing less than half as much as the original sensor, the new unit promises the additional economies of low maintenance and replacement costs on the basis of its durable performance in rifle firing tests. One unit continued to operate even after sustaining a direct hit.

Problem Status

This is the final report on this part of the problem.

Problem Authorization

NRL Problem S02-36.401
NTEC Work Request WR 1-0091 of 25 Mar 1971

Manuscript submitted 1 May 1973

A RELIABLE PIEZOELECTRIC BALLISTIC IMPACT DETECTOR

Introduction

A piezoelectric device that can be used as the sensor in the Army's hit detector system for rifle and tank firing ranges has been developed in cooperation with the Army Participation Group of the Naval Training Equipment Center (NTEC).

The original piezoelectric disk transducer used in this system performs well under certain conditions but its relatively high cost and lack of adaptability to changed target arrangements limit further applications of it. The most serious limitation of the existing system is that the sensor works well only when installed on the sheet metal target for which it was designed; therefore, plans to reduce costs by using cheaper target materials necessitated a new sensor. Also, its relatively delicate construction results in a high failure rate when it is used under the severe environmental conditions on the firing range. Because of its extreme sensitivity, this sensor must be mounted on the target with particular care to prevent stresses on the crystal that produce a false indication of a hit. A special mounting assembly designed for this sensor is particularly bothersome to install because it requires six accurately spaced holes in the target.

It was not unexpected that most of the experimental sensor models performed better than the original sensors in many respects. It was surprising, however, that the best of the experimental models was superior in every respect and, in addition, could be manufactured for a lower cost.

Design Constraints

Because the new detector was intended for use with the existing electronics of the Army system, specific design requirements were stipulated. The sensor assembly was to be capable of detecting impulses of projectiles penetrating the target, and the resulting signals were to be acceptable to the existing electronic hit-scoring circuitry. The sensor was to be designed for projectiles ranging in size from small arms to 155-mm cannon and was to be capable of discriminating against acoustic shock waves, muzzle blast from a range of 100 yd, and impacts of debris thrown at the target by near misses and rounds that fall short of the target. The mounting point for the sensor was restricted to the

lower edge of the target, but more than one sensor could be used if it was necessary. The target material was to be corrugated polyethylene. (A particular target material was not specified at first. Polyethylene was selected by NTEC after preliminary tests with plywood.)

Theoretical Considerations

It was necessary first to determine the approximate ranges of various parameters of the existing and required transducers. The input amplifier response was measured by inserting a 1-cycle sinusoidal pulse and increasing the pulse amplitude until the electronic system indicated a hit. Figure 1 shows threshold voltage amplitude as a function of frequency for the three ranges of attenuation provided by the amplifier to compensate for various sizes of projectiles. Results of some preliminary accelerometer measurements on the test range indicated that most of the unwanted noise picked up by the existing detection system was in the frequency range below 10 kHz. Specific acoustic impedance (ρc) and quality factor for samples of plywood and polyethylene target materials then were measured with a Brüel and Kjaer complex modulus apparatus (Table I). Results of the attenuation measurements for transverse and longitudinal waves in polyethylene are shown in Fig. 2.

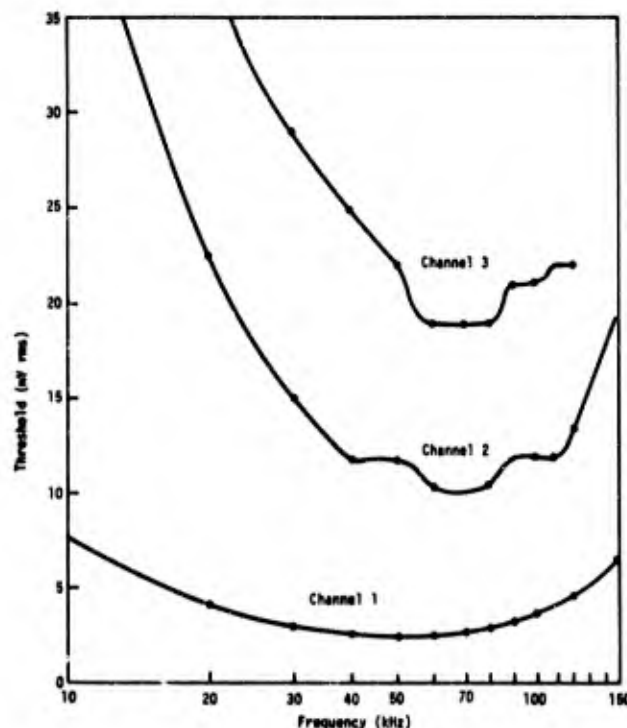


Fig. 1. Threshold voltages of input amplifier channels (1-cycle pulse).

Table I. Target materials parameters

Material	c_L (m/sec)	ρ (kg/m ³)	ρc_L (N·s·m ⁻³ ×10 ⁶)	Quality factor
Plywood	4210	5500	23.15	78
Polyethylene	2183	948	2.069	30
Eccobond (epoxy)	1723	1100	1.895	60

Two types of waves were considered in the analysis of target response characteristics because projectile impacts cause the target to respond transversely, thus exciting transverse (bending) waves; penetration by a projectile also causes expansion of the target material, setting up longitudinal (compressional) waves away from the point of impact [1,2].

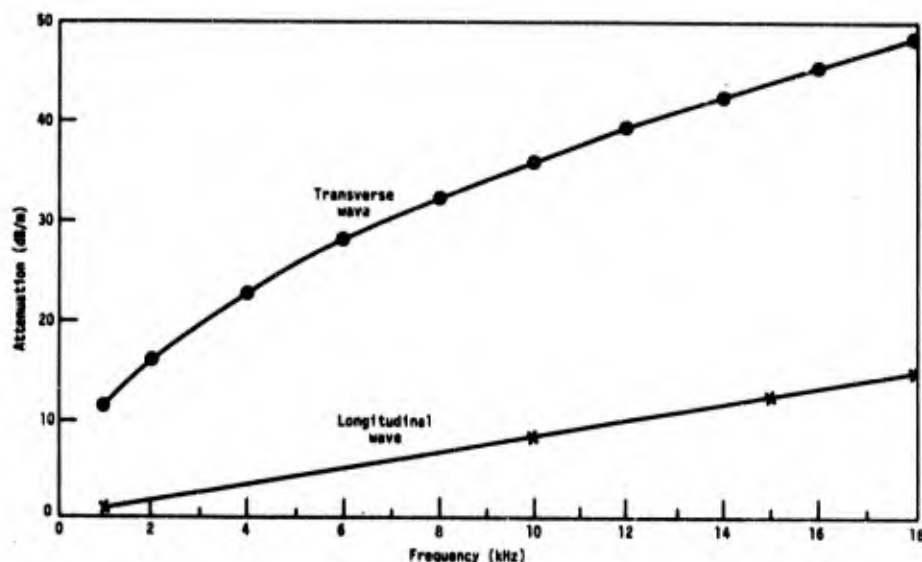


Fig. 2. Attenuation of longitudinal and transverse waves in polyethylene target material; $Q = 30$ at 22°C .

The speed of the transverse wave, according to Lindsay [3], is

$$c_B = [Y/3\rho(1 - \sigma^2)]^{1/2} (\pi ft)^{1/2}, \quad (1)$$

where Y is Young's modulus, ρ is density, σ is Poisson's ratio, f is frequency, and t is thickness of the target material.

Lindsay [3] gives the speed of the longitudinal wave as

$$c_L = [Y/\rho(1 - \sigma^2)]^{1/2}, \quad (2)$$

and the attenuation per wavelength for the longitudinal wave as

$$A = k\alpha = df\alpha/c_L = df\alpha/[Y/\rho(1 - \sigma^2)]^{1/2}, \quad (3)$$

where k is the wave number, α is the attenuation constant, and d is the distance from the point of impact to the transducer.

Attenuation in decibels per wavelength is given by $\alpha = 27.3/Q\lambda$ [4]. The number of wavelengths from the point of impact to the transducer is d/λ , and $\lambda = c/f$; therefore, $d/\lambda = df/c$. The attenuation per unit distance for transverse waves thus is $A_B = n\alpha = df\alpha/c_B$, where $n = d/\lambda$.

Similarly, for longitudinal waves, $A_L = df\alpha/c_L$.

Because of the relatively higher attenuation of transverse waves in the polyethylene target material, several experimental transducers were designed with resonance frequencies in the range 10 to 20 kHz to evaluate their response to longitudinal waves. Preliminary field tests with a plywood target indicated that the most satisfactory design was one that contained a ferroelectric ceramic ring, thickness polarized, MIL-STD-1376 (SiPS) Type I, 5.72 cm O.D. by 3.175 cm I.D. by 0.365 cm thick. Berlincourt, Curran, and Jaffe [5] give the following equation for the radial resonance frequency of this type of ring:

$$f_0 = (1/2\pi)(a^2\rho C_{11}^E)^{-1/2}, \quad (4)$$

where a is the mean radius (2.22×10^{-2} m²/N), ρ is the density

(7.5×10^3 kg/m³), and C_{11}^E is the compliance modulus (12.3×10^{-12} m²/N). The resonance frequency of the unloaded freely vibrating ring was 23.6 kHz, which was reduced to the exact frequency required (16 kHz) by cementing a stainless steel washer 6.35 cm in diameter by 0.635 cm thick to the ring. After the ring was encapsulated in epoxy potting compound, the resonance frequency dropped to 15 kHz.

Evolution of the Design

After a satisfactory transducer element had been selected on the basis of purely theoretical considerations, several experimental sensors were designed with the simplest possible mechanical mounting for which the number of fasteners was reduced to the absolute minimum of a single bolt. This type of mounting requires little more than two washers and

insulation to attach the sensitive element to the target. The bolt is inserted through a single drilled hole and the assembly is secured by means of a hand-tightened wingnut, which reduces the possibility of overtightening or producing an unbalanced stress on one part of the element.

The design of the best of seven experimental sensors was modified to produce four other experimental sensor configurations for further evaluation. A subsequent test of these sensors showed that one design was capable of detecting more than 90 percent of ballistic impacts and that it discriminated against almost all false signals.

Test Procedure

All USRD measurements of responses to ballistic impacts were made at the small arms range of McCoy Air Force Base and the Marco Gun Club of Orlando. Because it was not possible to investigate all possible target and shooting conditions at these sites, a limited test program was designed to measure the physical responses of the targets, the present sensor, and new experimental sensors to impulses generated by high-velocity 30-06 projectiles fired from a range of 100 yd. A block diagram of the instrumentation used for these measurements is shown in Fig. 3. Figure 4 shows a typical range installation of a group of experimental sensors on the bottom foot of a target, with the hit-scoring unit located nearby. Figure 5 shows the storage oscilloscope, the eight-track instrumentation recorder, and other equipment used during a test run.

The same general procedure was used for both the preliminary tests with the plywood target and later tests with the polyethylene target. One-foot squares were marked off on the target with electrical tape to facilitate identification of impact areas, and the sensors were fastened to the target in the bottom row as shown in Figs. 4 and 6. After the instrumentation was connected, an expert marksman called out one of the target square numbers and fired at least one round at it; after each shot, an observer (with a spotting telescope focused on the indicator light of the hit-scoring unit) made an oral report of the result and another observer checked the target through his telescope and reported which square was hit. Oral reports were recorded on the voice channel of the data tape, and the sensor data were recorded on the remaining AM channels (to at least 50 kHz). Samples of sensor data also were recorded by the storage oscilloscope for subsequent analyses of signal levels and duration.

Transducer sensitivity to air-coupled acoustic noise from muzzle blast and the acoustic shockwave traveling ahead of the projectile was determined by recording data in the same manner as for the preceding test shots but while firing in the general direction of the target and deliberately missing it. Each transducer was checked in this manner for the firing ranges 25, 50, and 100 yd.

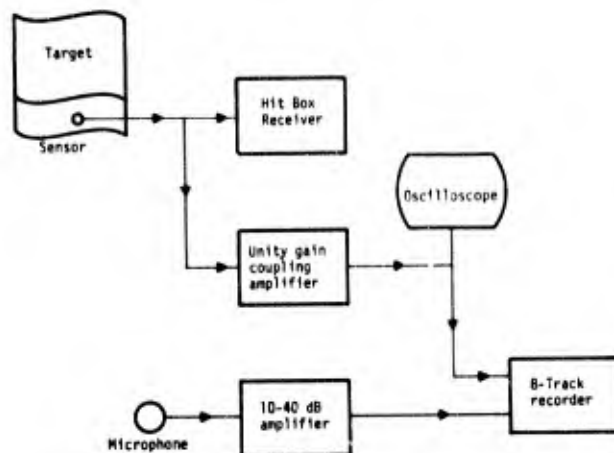


Fig. 3. Block diagram of hit detector instrumentation.

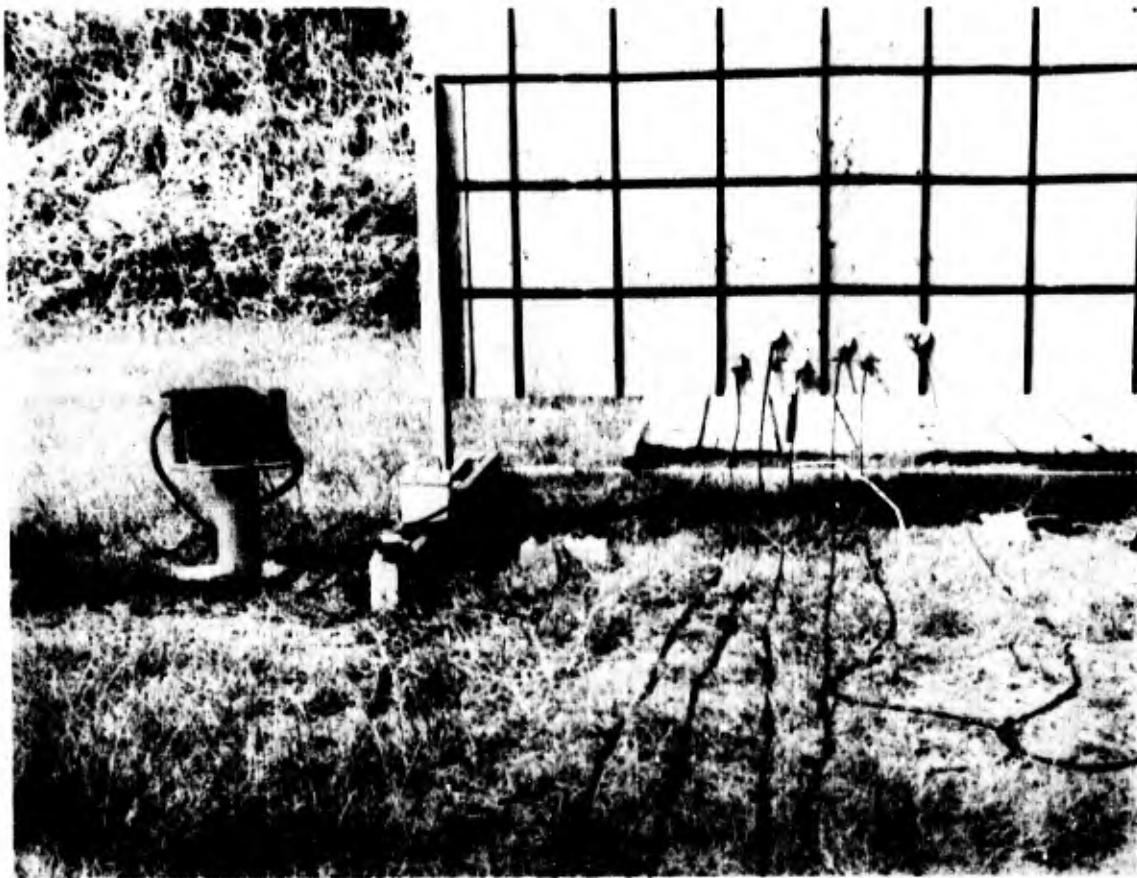


Fig. 4. Typical target installation. Transducers are mounted in bottom row of the target; scoring unit is at left.

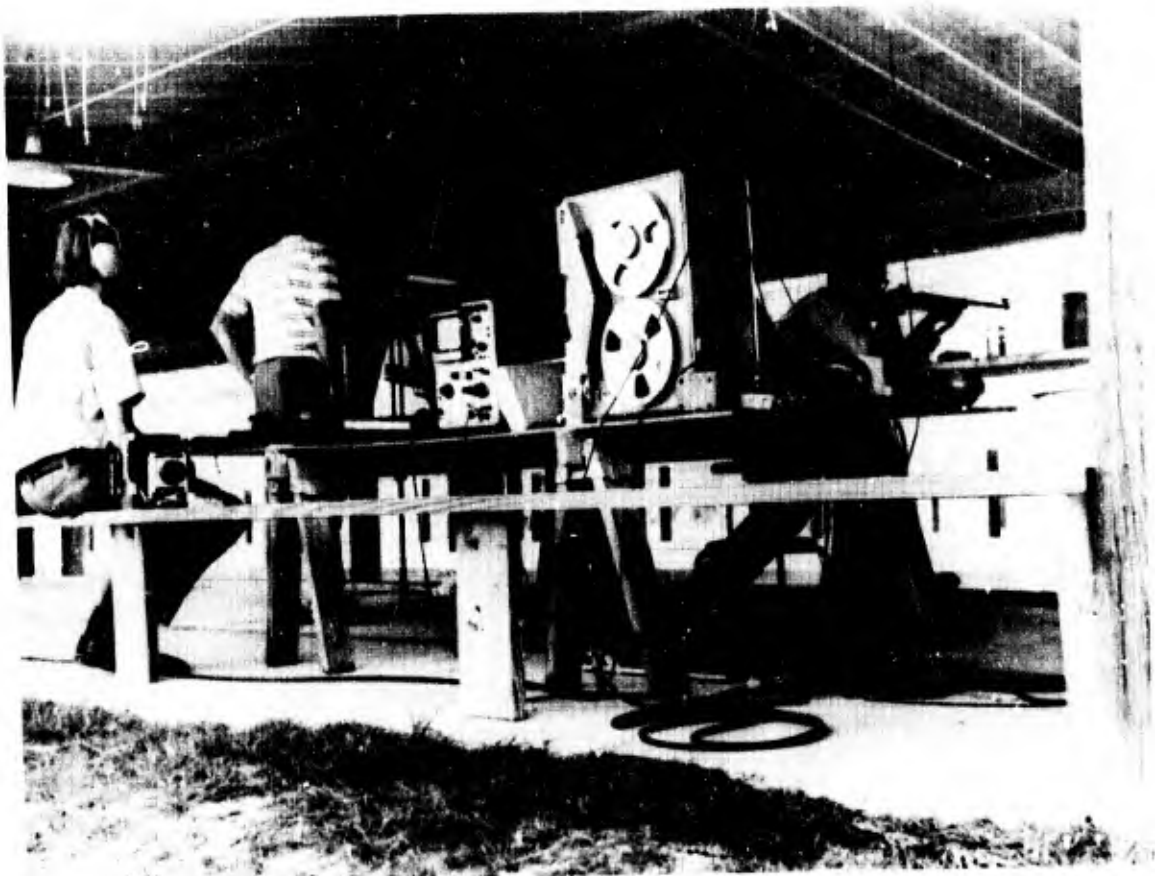


Fig. 5. Hit box instrumentation near the test range firing line.

The combined impulse response of the target and the sensor was determined by observing the results from the sensor data tape on the screen of the storage oscilloscope, converting selected data from the time domain to frequency domain by a Federal Scientific Ubiquitous UA14 Analyzer, and plotting the results with an X-Y plotter (Fig. 7). Reference signals of 1.0 and 0.5 V at 10 and 15 kHz, respectively, were recorded at the beginning of each data tape track to provide absolute output values. The channel 4 voice monitor was used to aid in establishing the identification of each pulse shot.

Results

The experimental sensor designated as X6 detected about 90 percent of the ballistic impacts; the other experimental sensors detected from 10 to 75 percent. The original Army sensor was too sensitive to muzzle blast and other vibrations to permit an accurate determination of its detection capability. In later measurements made with the four improved X6 type sensors mounted on a polyethylene target, one of the new sensors detected nearly 100 percent of ballistic impacts and the other three sensors detected about 80 percent of the hits.



Fig. 6. Inspecting transducer installation on polyethylene target.

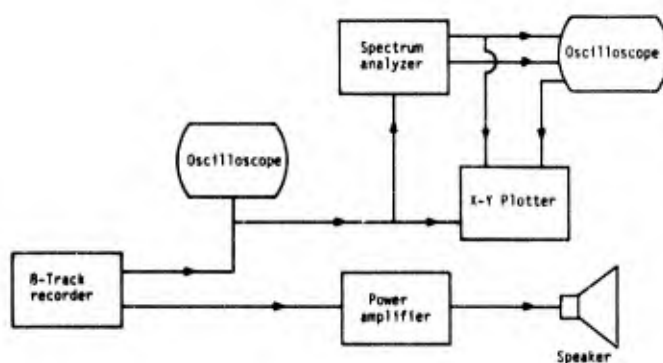


Fig. 7. Block diagram for spectral analysis of hit detector data.

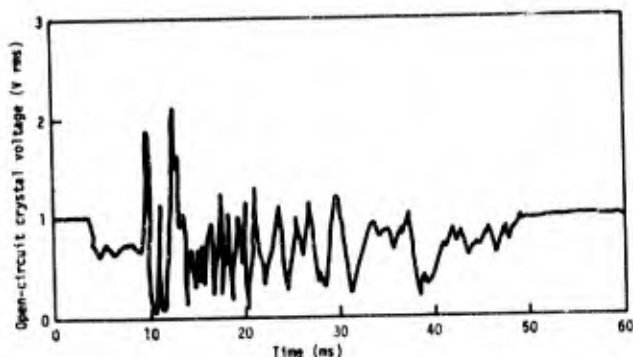


Fig. 8. Time function for 30-06 projectile impacts in target column 5.

A typical time function and the associated frequency spectrum for a projectile impact on the target as detected by the X10 sensor are shown in Figs. 8 and 9. Figure 10 shows the relationships between the vertical distances from points of impact to the sensor and the amplitudes of the characteristic frequency peaks (10, 12.5, and 15 kHz) observed in the X10 spectra for these measurements. It appears that the 10-kHz frequency peak is the best indicator of the vertical position of a hit because interference caused by reflections from the edges of the target was less pronounced. Attenuation coefficients were computed for selected data points that appeared in Fig. 8 to be least affected by boundary conditions. Normalized attenuation for the frequencies 10, 12.5, and 15 kHz shown in Fig. 11 are in reasonable agreement with the calculated values shown in Fig. 2. This procedure shows that meaningful information can be obtained from samples of various target materials to establish transducer design criteria so that the extent of testing can be minimized.

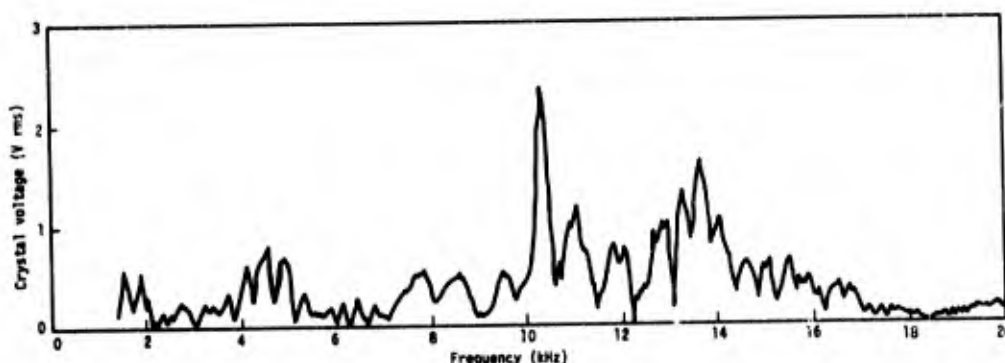


Fig. 9. Frequency spectrum for 30-06 projectile impacts in target column 5.

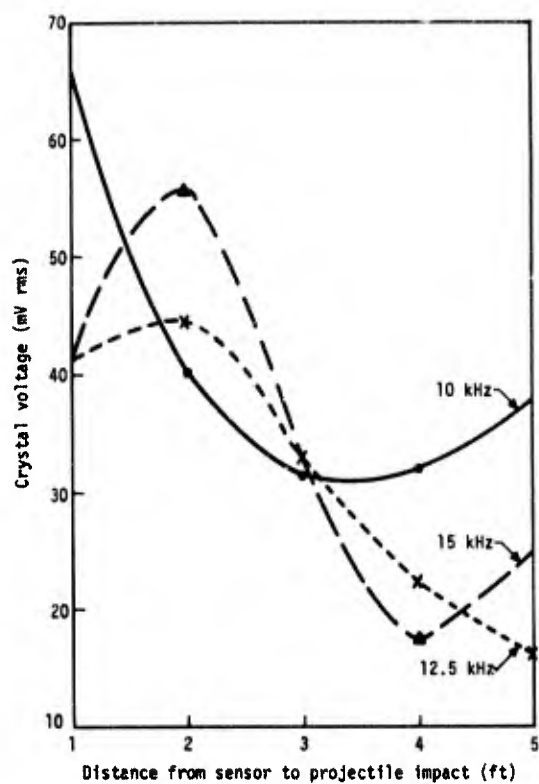


Fig. 10. Open-circuit crystal voltage response of G39 sensor at various vertical distances from points of projectile impacts.

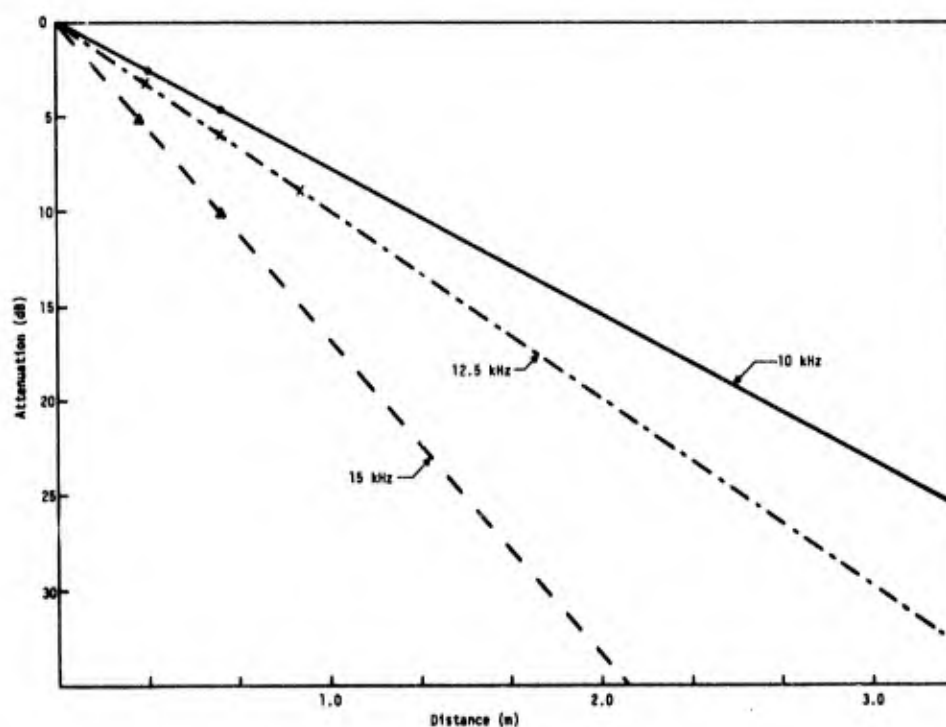


Fig. 11. Normalized attenuation as a function of distance for the frequencies 10, 12.5, and 15 kHz.

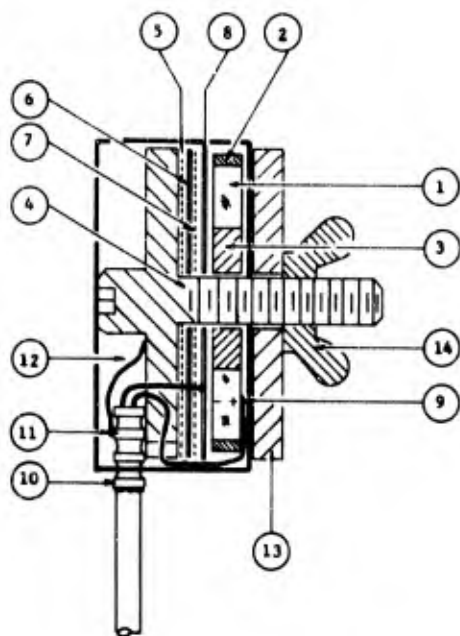


Fig. 12. Sectional view of USRD type G39 transducer: (1) ferroelectric ceramic element, (2) Corprene outer ring, (3) Corprene inner ring, (4) mounting subassembly, (5) epoxy resin, (6) fiberglass resin, (7) epoxy resin, (8) negative electrode foil, (9) positive electrode foil, (10) cable assembly, (11) copper ferrule, (12) epoxy resin, (13) stainless-steel washer, (14) wingnut.

Construction of the G39 Transducer

Figure 12 is a sectional view of experimental sensor X10, which is officially designated USRD type G39 transducer. This assembly consists of three separable units that are taken apart as shown in Fig. 13, then reassembled for mounting on a target: transducer section, stainless-steel washer, and stainless-steel wingnut. The transducer



Fig. 13. USRD type G39 transducer.

section includes the ceramic element, insulation, and electrical connectors encapsulated in epoxy potting resin together with the mounting subassembly, which is fashioned from a stainless-steel washer silver-soldered to the shoulder of a 3/8-24x1 1/2 in. Allen-head machine bolt. Corprene cylinders fitted closely to the inner and outer cylindrical surfaces of the ceramic element provide acoustical shielding, but permit the element to vibrate or deform freely with minimal damping. Mechanical parameters of the epoxy resin closely approximate those of the new polyethylene target, thus assuring maximum coupling of impact pulses from the target to the sensitive element.

Electrical measurements of the G39 at the end of the standard 3-m cable indicate the following resistances: high lead to low lead, >30 G Ω ; high lead to shield, >10 G Ω ; and low lead to shield, >10 G Ω . The capacitance measured with a 1-kHz bridge has a nominal value of 3354 pF from the high side to the low side, with a dissipation of <1%. The resonance frequency and typical impedance for the G39 (without external mounting washer) are shown in Fig. 14.

Conclusions

Test results for the USRD G39 transducer indicate that it satisfies all the performance requirements specified for the new hit sensor. Although durability tests were not performed, none of the experimental transducers of this general type sustained damage during gunnery range tests. (One unit continued to operate properly after receiving a direct hit.) Cost estimates show that the G39 can be produced in quantity for less than half the cost of the sensor now being used (Appendix A).

The time and frequency spectra for projectile impacts on the polyethylene target show a wide variation in the signal amplitude measured across any horizontal line. A possible explanation may be that the vertical corrugations in the target material present different effective thicknesses to projectiles passing through curved surfaces depending on the relative angle between the target cross section and the path of the projectile. The general trend of the results appears to support this explanation.

Acknowledgements

The authors wish to express their appreciation for the assistance and cooperation of the Marco Gun Club of Orlando, particularly that of Mr. Allan C. Tims, who did the expert shooting in the range test program. Special acknowledgement is due the McCoy Air Force Base for the use of its small arms range.

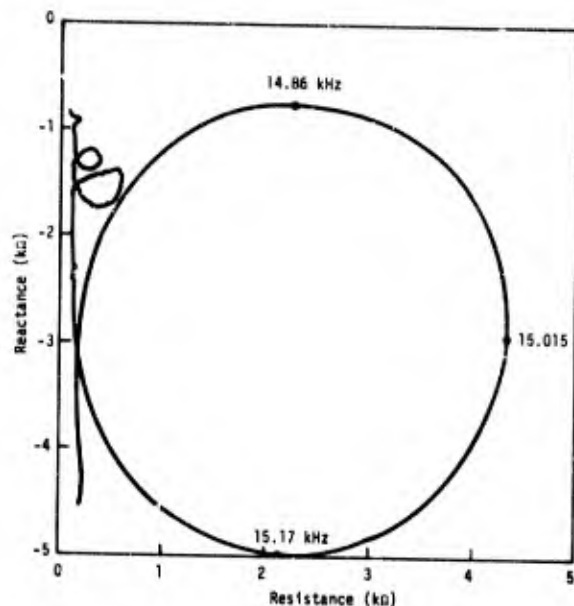


Fig. 14. Typical impedance of G39 transducer (without external mounting washer).

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Appendix A

Cost Estimate for Fabrication of 300 USRD Type G39 Transducers

Item	Unit cost	Cost per 300 units
PZT-4 ceramic element	\$ 2.51	\$ 753.00
Washers, 2-1/2-in., set of 2 type 304 ss	1.33	399.00
Machine bolt, 3/8-24 X 1-1/2-in. type 304 ss	0.39	117.00
Cable, 2-conductor, shielded (units of 500-ft rolls)	41.00	246.00
Wingnut	0.20	60.00
Connectors	3.00	900.00
Epoxy resin (1-qt units)	15.00	375.00
Labor, assembly	15.00	5,250.00
Total cost, 300 units		\$8,100.00
Cost of 1 unit in quantities of 300	\$27.00	